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Influence of Ventilation Status on Combustion Characteristics of Coach Fire

CHEN Jie[a,b,*] , YI Lang[a,b]

[a]Institute of Disaster Prevention Science and Safety Technology, Central South University, Changsha,410075, China
[b]Key Laboratory of Operation Safety Technology on Transport Vehicles, Ministry of Transport, Beijing,100088, China

Abstract

Based on the principle of oxygen consumption, relationship between heat release rate of coach fire and ventilation factor is studied. The peak heat release rate of coach fire is estimated under four typical ventilation conditions: one window, two windows, four windows and all windows of the fire coach are opened, respectively. Results were compared with the predictions by traditional empirical formulas for flashover in confined space. A suitable calculation method for forecasting the heat release rate of coach fire is presented. CFD means were also applied to simulate and analyze the impact of the ventilation factor on the burning characteristics of coach fire. The results indicate that the calculation method can predict the heat release rate of coach fire well. The peak heat release rate of coach fire is proportional to the ventilation factor. The calculation results are 6.3MW, 8.4MW, 12.6MW and 39.7MW and simulation results are 6.5MW, 9.9MW, 14.8MW and 39 MW respectively under different ventilation conditions in this study. The results also show that the heat release rate and of coach fire increases with the increase of ventilation factor.

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Keywords: Coach fire; Heat release rate; Ventilation factor; CFD simulation.

1. Introduction

Because of small space and full of combustibles, once a fire occurs in a coach the fire will growth rapidly and inevitably lead to flashover with good ventilation condition. The occurrence of flashover indicates that the fire in the coach is the most dangerous. Temperature, heat release rate and smoke generation increases to maximum rapidly. It is extremely hard for the personnel in the coach to evacuate and survive, severe casualties is the common result. Therefore, studying the development of fire in coaches is of significant theoretical and practical value.

Due to high cost and difficulty of experimental condition control, few full-scale experiments on combustion characteristics of coach fire have been conducted. Sweden National Testing and Research Institute (SP) has developed a series of researches on bus and coach fire since 1990. The results show that heat release rate of coach and bus fire can reach up to 30 MW [1]. In 1995, Ingason [2] measured the heat release rate of a 12 m long Volvo school bus with 40 seats in a tunnel fire experiment and got the peak heat release rate of 29 MW. In 1999, Peacock [3] made two fire tests with a mini-type coach based on the oxygen consumption principle, measured the heat release rate, and recorded the temperature and gas concentration variation curve. In 2004, Mangs etc [4] conducted a full-scale fire experiment on medium-type coach equipped with a spare tire and 30 liters gasoline in open space, and obtained the heat release rate and temperature curve. Affecting factors on development of coach fire are various including ventilation conditions, fire source parameters, flammability properties of material and so on. Among them, ventilation condition is a key parameter. This study focuses on analyzing the effect of ventilation conditions on coach fire combustion characteristics through theoretical analysis and numerical simulations, Results of the study can provide theoretical reference for numerical study on coach fire and fire protection of coach fire in practice.

* Corresponding author. Tel.: +86-731-82656625.
E-mail address: chenjie.20071007@163.com

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2. Theoretical analysis on heat release rate of coach fire

2.1. Flashover prediction model for critical heat release rate

Coach is typical confined space with abundant combustibles. As fire develops in an enclosure, burning type in a coach fire often transforms from fuel-control to ventilation-control with flashover as the transition event. After the occurrence of flashover, coach fire turns into full development stage in which the heat release rate maintain nearly steady value for a period of time till the combustion abates. In the ventilation-control burning stage, combustion in the coach fire depends on ventilation conditions [5, 6]. It is considered that the heat release rate of fire in full development stage equals that of flashover. Prediction of critical heat release rate of flashover in enclosure can be found in literatures and are as follows:

(1) Babrauskas's model

Based on energy balance of the upper layer of hot gases in an enclosure fire, Babrauskas deduced a calculation expression for estimating critical heat release rate of flashover [7]:

$$\dot{Q}_c = 750A(H)^{1/2} \tag{1}$$

where $\dot{Q}_c$ is the critical heat release rate required for occurrence of flashover(kW), A is area of opening (m2), and H is the height of opening (m). The factor $A(H)^{1/2}$ is ventilation factor (m 5/2).

Thomas's model use the principle of energy conservation in enclosure fire, Thomas achieved a predicting model on critical heat release rate of flashover [8]:

$$\dot{Q}_c = 7.8A_T + 378A(H)^{1/2} \tag{2}$$

Where A_T is the total area of effective surface (m^2).

(2) McCaffrey's model

Considering thermal inertia of wall materials, McCaffrey proposed a calculation method on critical heat release rate required to induce flashover in enclosure fir^e [9]:

$$\dot{Q}_c = 610(h_k A_T A(H)^{1/2})^{1/2} \tag{3}$$

Where hk is effective heat transfer coefficient between the gas and walls and ceiling of the room (kWm-2K-1).

All of the above models assume flashover occurs once the hot layer temperature exceeds 500-600 °C.

2.2. Estimation of heat release rate based on oxygen consumption

Technology of estimating heat release rate by measuring oxygen consumption rate has been wildly used in fire research. According to Huggett's [10]] theory, for most organic matter the heat release rate of burning is proportional to the oxygen consumption rate:

$$\dot{Q} = E\dot{m}_o \tag{4}$$

Where $\dot{Q}$ is the heat release rate (kW), $\dot{m}_o$ is the consumption rate of oxygen(kg/s), E is the proportionality coefficient, generally 13.1MJ/kg, with the deviation within 5 %.

Gas in enclosure can be considered to be fully mixed in post-flashover stage [11]. Considering an enclosure with an opening as shown in Fig.1. H is the height of opening (m), $\dot{m}$, ρ and h are values of mass flow rate (kg/s), density(kgm-3) and the height(m), respectively. Subscripts a and g denote fresh air and hot gas, respectively.

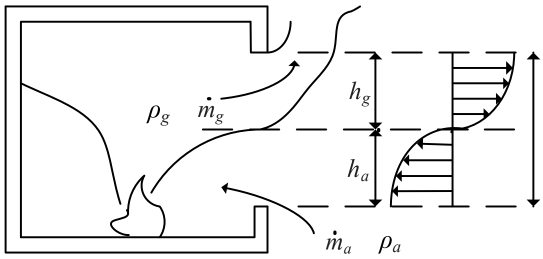

Fig.1. Driving figure of buoyant flows across the vent of compartment fire

Gas flow rate out and in through the opening, $\dot{m}_g$ (kg/s) and $\dot{m}_a$ (kg/s), can be calculated using the following equations:

$$\dot{m}_g = \frac{2}{3} C_d W \rho_g \left(2(\rho_a - \rho_g) g / \rho_g \right)^{1/2} h_g^{3/2} \tag{5}$$

$$\dot{m}_a = \frac{2}{3} C_d W \rho_a \left(2(\rho_a - \rho_g) g / \rho_a \right)^{1/2} / h_a^{3/2} \tag{6}$$

Where Cd is discharge coefficient(0.6~0.9, commonly 0.7), g is the gravitational acceleration(9.81 m/s^2), W is the width of the opening (m).

Ignoring the mass loss of fuels, $\dot{m}_a$ is assumed to be equal with $\dot{m}_g$, $\dot{m}_a$ can be expressed as:

$$\dot{m}_a = \frac{2}{3} C_d A(H)^{1/2} \rho_a (2g)^{1/2} \left(\frac{(\rho_a - \rho_g)/\rho_a}{\left[1 + (\rho_a/\rho_g)^{1/3}\right]^3} \right)^{1/2} = \frac{2}{3} C_d A(H)^{1/2} \rho_a (2g)^{1/2} \delta \tag{7}$$

Where δ is called density factor. In most fire scenarios in confined space, δ is approximately equal to 0.214. For coach fire, the mass fraction of oxygen in air is 23.1%, under the assumption that all air entering the carriage is completely consumed, using the oxygen consumption principle the maximum heat release rate $\dot{Q}_{\max}$ (kW) in coach fire can be calculated by:

$$\dot{Q}_{\max} = 1606 A(H)^{1/2} \tag{8}$$

3. Numerical simulations

3.1. Coach model

The layout of coach model is shown in Fig.2. The inside dimensions of the coach is 10.15 m long x 2.4 m wide x 3.4 m high, and the effective height in carriage is 2 m. The main combustibles include the seats, curtains and other interior materials. The main combustible materials and their thermal physical parameters are listed in Tab.1 and Tab.2 [12]. By a comprehensive consideration of the computing time and accuracy, mesh size in each simulation case with FDS software package is 0.1m x 0.1m x 0.1 m.

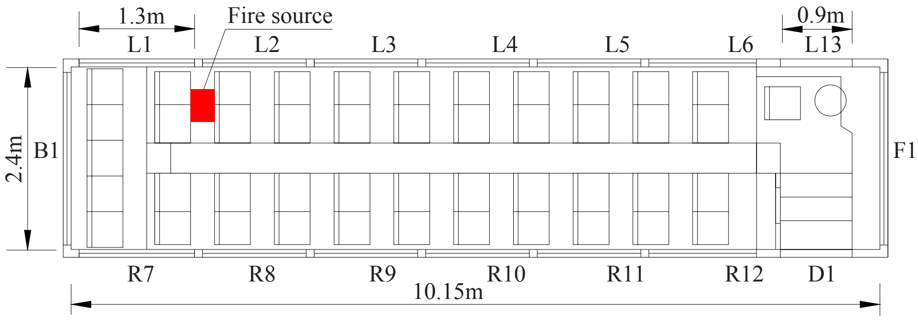

Fig.2. Plan of coach

Tab.1 List of main combustible materials in coach

Component	Material
Seat	Fabric & Polyurethane foam
Window curtain	Fabric
Wall & Ceiling	PVC & Steel
Baggage rack	PVC
Floor	Plywood & Steel
Instrument desk	ABS & Polyurethane foam

Tab.2. Properties of Materials

Material	Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat (kJ/kg·K)	Temperature to ignition (℃)	Reaction heat (kJ/kg)	Combustion heat (kJ/kg)
Fabric	100	0.1	1	350	3000	15000
Polyurethane foam	40	0.05	1	350	1500	30000
PVC	1380	0.16	0.9	507	2000	19000
Plywood	510	0.12	2.1	400	840	18700
ABS	1050	0.18	1.047	—	—	—
Toughened glass	2500	0.05	0.84	—	—	—
Steel	7850	45.8	0.46	—	—	—

3.2. Fire source

It is assumed the coach was ignited by 1 kg gasoline on the floor, as shown in Fig.2. Heat release rate of the igniting source increases to 865 kW from 0 kW in 68 s, then kept stable for 18 seconds, and decays linearly to 0 at 106 s [13].

3.3. Ventilation

In order to study the effect of different ventilation condition on coach fire, four cases were considered in the simulations as listed in Tab.3. The coach stops immediately after catching fire, and the door is opened. The environment temperature is set at 20 °C.

Tab.3 Ventilation condition of coach

Case	Ventilation condition	$A(H)^{1/2}$ ($m^{5/2}$)
Case1	Window R10 break 20 s after ignition	3.9
Case2	Windows R8 and R10 break 20 s after ignition	5.2

Case3	Windows L2, L4, R8 and R10 break 20 s after ignition	7.85
Case4	Windows break when gas temperature near the glass reaches 400℃[14]	24.76

4. Discussion of results

Variations of heat release rate in 4 simulation cases are plotted in Fig.3. The figure shows that the ventilation condition determines the heat release rate. With the improvement of the ventilation conditions, the peak heat release rate increases, also the time reaching peak value is shortened. In the early period oxygen in carriage was enough to maintain burning, burning are fuel-controlled, and the curves are almost the same. The combustion turns into ventilation-control type at about 70 s. In case1 and case2 ventilation factors have obvious inhibitory effect on combustion. After heat release rate reach a crest at about 60s and then rise again. Heat release rate drop rapidly and sustain relatively steady values of 1.8 MW and 2.5 MW respectively from 60 to 200 s. It is because the combustion produces a large number of hot smokes in fuel-control stage, which intensifies inner pressure and hinders the fresh air from flowing into the coach. Heat release rate drops for lack of oxygen, and the inside temperature and pressure also decreases subsequently. Along with the decrease of inner pressure, air exchange between inner and outer of the coach is improved, more oxygen enters and combustion begin to be intensified. Heat release rate reaches the peak value of 6.5MW at 310s in case1, and reaches the peak value of 9.9MW at 280s in case2. Combustion in case3 is also controlled by ventilation factor. At 180 s, heat release rate reaches to the peak value of 14.8 MW. Ventilation condition in case4 is good, therefore, combustion in case4 is the most intensive. The heat release rate in case4 reaches a maximum value of 39MW at 120 s.

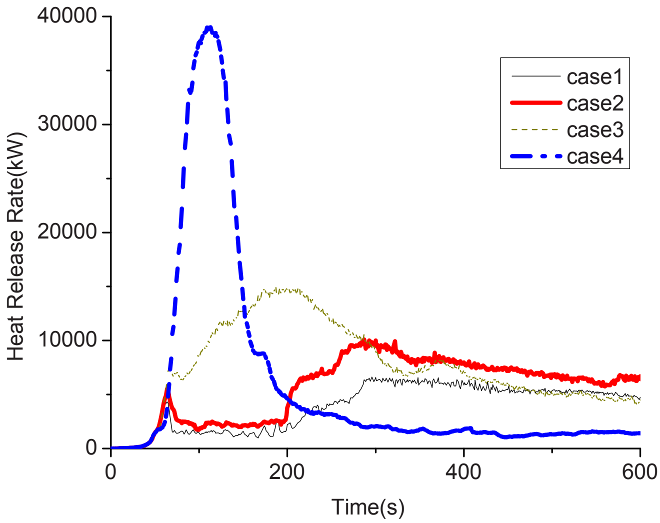

Fig.3. Heat release rate curves

Tab.4 presents the values of heat release rate predicted by empirical formulas and CFD simulation. Results calculated by the above 4 kinds of predicting model are of great discrepancy. It is found that the calculation results with oxygen consumption principle are very close to those by numerical simulations. Therefore, the model is proposed to predict peak heat release rate of coach fire under different ventilation conditions, though more experimental work is still need conduct to validate it.

Tab.4 Heat release rate calculated by different methods

Calculation method	Heat release rate $\dot{Q}$ (MW)			
	Case1	Case2	Case3	Case4
Babrauskas	2.9	3.9	5.9	18.6
Thomas	2.3	2.8	3.0	10
McCaffrey	38	43	53	91
Oxygen consumption principle	6.3	8.4	12.6	39.7

Numerical simulation	6.5	9.9	14.8	39

5 Conclusions

Theoretical analysis and numerical simulation are carried out to study the development process of coach fire in different ventilation conditions. Based on oxygen consumption principle, a predicting model for peak heat release rate in coach fire is proposed. Compared with results calculated by other traditional flashover models and numerical simulation, proposed model can effectively estimate the peak heat release rate in coach fire.

Ventilation conditions directly affect fire spreading and the duration of combustion in coach fire. Burning in the coach is more intensive and burning time is shorter with big ventilation factor, accordingly, the heat release rate and temperature is higher. In a good ventilation case, the maximum heat release rate of coach fire can reach up to 39 MW, temperature even is higher than 1300 ℃. Therefore, available safety evacuation time is relatively short. When a coach catch fire, increasing the ventilation is beneficial to smoke emission and personnel escape. But it also intensifies fire spreading, and leads to flashover quickly. So in the process of evacuation and suppression in coach fire, how to damage the glass windows to ensure passengers evacuating safely is very important for the coach design and fire rescue decision-making, and still needs further research.

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